



SERC RT 18

Valuing Flexibility

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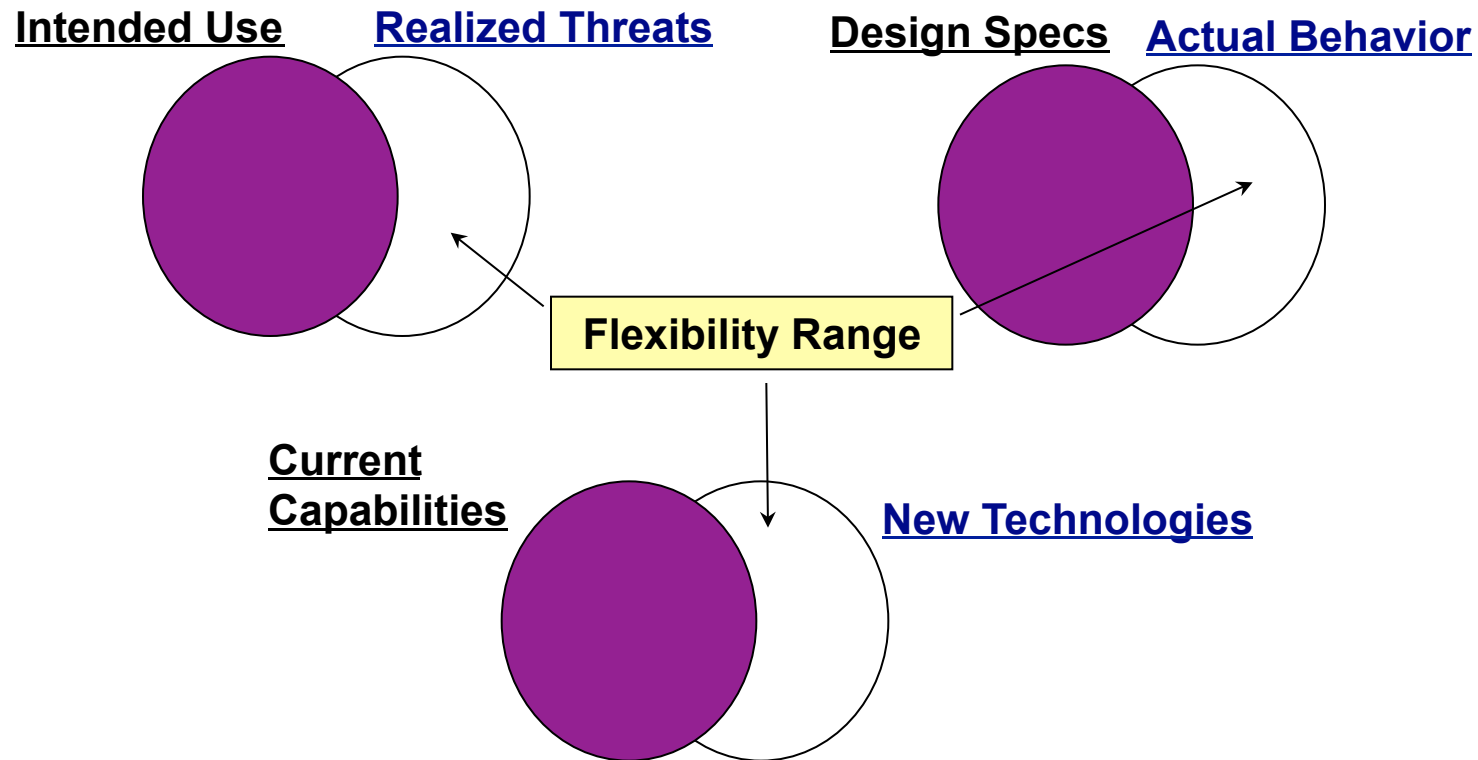
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- **RT-18 Overview**
 - Motivation, Goals and Tasks
- **Critical Review of Current State of Knowledge**
- **Exploring Methods for Valuing Flexibility**
 - Total Ownership Cost
 - Real Options/Knowledge Value Added
 - Common Use Case Study – Modular Munitions
- **Gaps, Plans and Priorities**
 - Gap Analysis
 - Plans and Priorities
- **Input from Key Constituents**

What are we trying to do?

- **Primary objectives**
 - Develop convincing quantitative methods, processes, and tools (MPTs) for determining the value of flexibility in DoD contexts
 - Develop associated MPTs for cost-effectively improving flexibility in DoD contexts
 - Identify gaps in current approaches for valuing, improving and incorporating flexibility in the context of future DoD needs
- **Value-based definition of “flexibility”**
 - A system is flexible to the extent that it can be **cost-effectively modified** to meet new needs or to capitalize on new opportunities
 - “Cost” includes dollars, calendar time, critical skills, and other scarce resources (facilities, equipment, supplies, etc.). It also includes the costs of flexibility-induced decrements in other system attributes (performance, security, safety, usability, etc.)
 - “Effectiveness” includes improvements in military outcomes across a range of weighted scenarios, and cost avoidance (e.g., cost of delay)

Basic Issues in Valuing Flexibility



- **If you do not need it, it has no value**
 - Flexibility is needed only in presence of uncertainty
 - Characterizing downstream uncertainty is difficult (yet essential)
- **If you cannot afford it, you will not incorporate it**
 - Quantifying benefits – and cost of flexibility
 - Estimating current value of flexibility

How is it done today?

- **Several definitions and methods exist for valuing flexibility**
 - Many definitions are qualitative or descriptive
 - Current methods for valuing flexibility are not consistent with flexibility metrics, have unrealistic assumptions and do not work well with DoD measures-of-effectiveness
- **Several classes of MPTs for improving flexibility**
 - Modular and service-oriented architectures; domain ontologies; interoperability connectors; autonomy and adaptive control; agile methods; concurrent engineering; user programmability
- **Little unifying theory**
 - Or guidance on which MPTs work best in which situations
- **In practice, it is generally not done today**
 - Acquisition infrastructure optimized around fixed-price, build-to-spec
 - Temptation in evolutionary development to go easiest-first
 - With current infrastructure, leads to inflexible initial point solution
 - Flexibility is recognized as a desirable property of systems, but justification for expending additional resources to obtain flexibility is lacking

Tasks proposed in RT-18

- **Survey state-of-the-art in valuing flexibility**
 - Definition of flexibility
 - Metrics for quantifying flexibility
 - Approaches for valuing and incorporating flexibility
- **Capability to value flexibility (2 or 3 approaches)**
 - To handle foreseeable sources of change
 - Using monetizable metrics, such as total cost of ownership
 - Advanced methods for valuing flexibility for DoD relevant metrics
- **Validate MPTs using DoD case studies (2 or 3)**
 - Completed projects
 - Prospective projects
- **Gap analysis of current MPTs for valuing flexibility and DoD needs for future systems**
 - Research roadmap

Current state-of-the-art

Flexibility: Concepts, Metrics, Approaches

Measures
Counting number of choices
Number of options or system states affected
Graph theoretical measure
Entropy measures
Uncertainty and dispersion measures
Impacts on other -ilities

Enablers
Interoperability
Modularity
Product platforms
Adaptability factor
Standardization
Self-organizing systems
Reconfigurable components

Monetized Analysis
Total ownership cost
Real options
Insurance analysis
Risk analysis
Attribute tradeoff analysis
Cost of delay analysis
Product line ROI analysis

Incorporating Flexibility in Systems

Modularity

- Modularization of the system's architecture around foreseeable sources of change

Design for Adaptability

- System adaptation through feedback control mechanisms

Design for Changeability

- System design comprised of four strategic attributes: flexibility, agility, robustness, and adaptability

Acquisition Strategy

- Cultivate flexibility in the design process to some degree via acquisition strategies

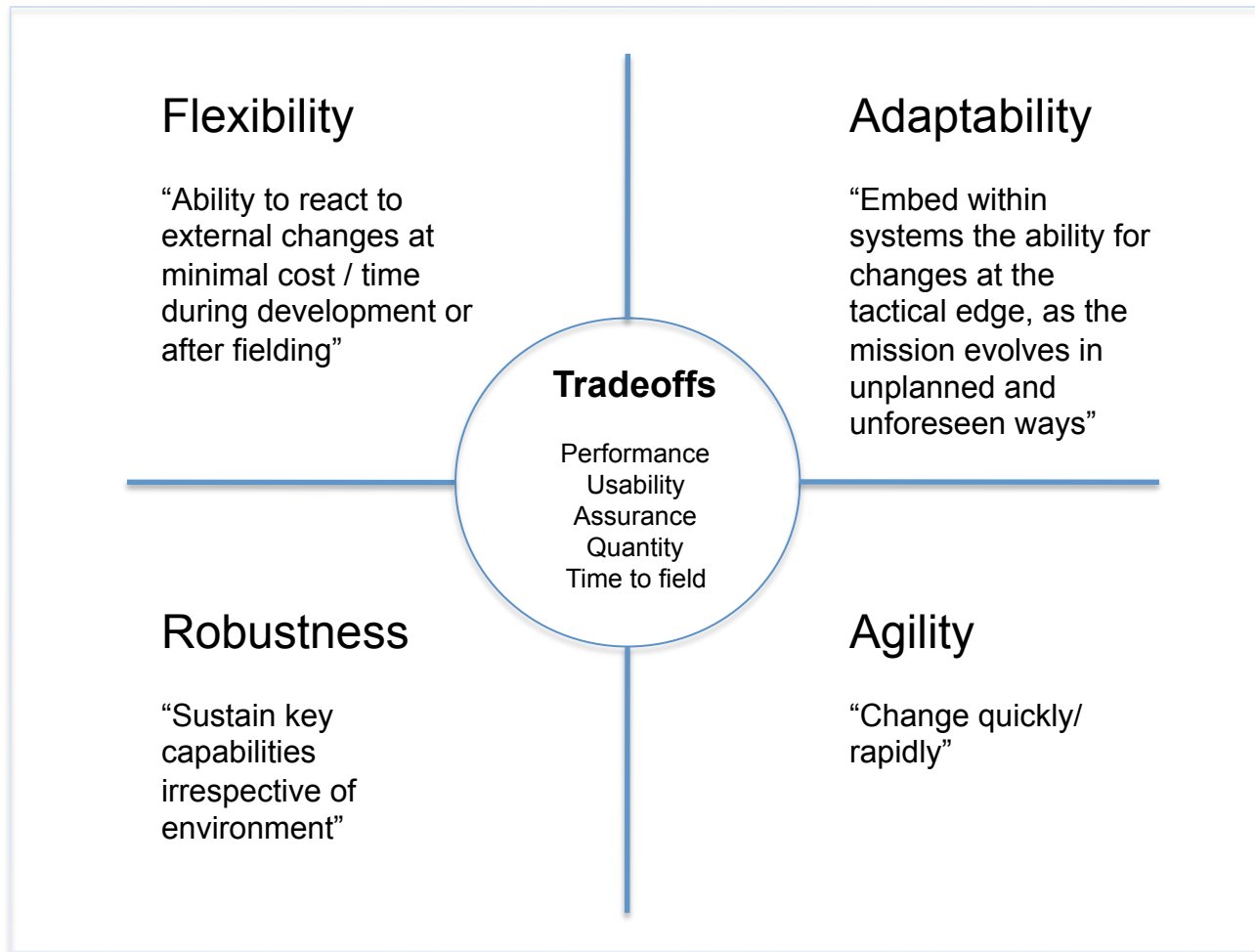
Methodology for Assessing the Adaptability of Products (MAAP)

- Identification of improvement potential in design through a priori applicability requirement knowledge

Open Architecture

- Extension of software domain ideas into hardware design by embedding knowledge and rules about possible product differentiations into products

Relation with Other *-ilities*



Classification Framework

Will the system change?

- change within the system
- accommodate change

Is the change foreseeable?

- known – knowns
- known – unknowns
- unknown - unknowns

What is the source of change?

- internal
- external

When may the change occur?

- before deployment
- after fielding

What measures of change efficiency apply?

- quantification of system change efficiency
- time, cost , ...

Classifying Current Work

FLEXIBILITY												
	System Change?		Measure(s) of Change Efficiency		Source of Change			Foreseeable?		When Change Occurs		Other
SOURCE	Yes	Not Necessarily	Quickly	Cost-Effectively	Int	Ext	Reqmnt	Known	Unk	Prior to Fielding	After Fielding	Related Terms
Thomke, 1997	"modifying a product"		"incremental cost and time"		x	x						
Roser, 1999	"change performance"		"minor time and costs"									
Schulz, 1999	"system to be changed"		"changed easily"									Component of Changeability
Bordoloi, 1999	"change states"											Efficiency and Adaptability
Olewnik, 2001	"changes in configuration"		"real-time"			x	x	x	x			Robustness and Adaptability are modes of Flexibility
Palani, 2003	"design changes"		"ease" of change									
Nilchiani, 2003	"increasing control capacity"					x			x			
Banerjee, 2004		"support new functions"										
Nilchiani, 2006		"ability to respond"	"timely"	"cost-effective"	x	x						
Qureshi, 2006		"responsive-ness"	"degree of responsiveness"									
Keese, 2007	"redesign"		"quickly"	"inexpensively"			x		x			

State of Knowledge

- Lack of consistency in flexibility definitions
- Confused with other “-ilities”
- Lack of connection between flexibility and value
- Lack of relationship between flexibility and design variables
- Lack of “scholarly maturity”
“concept of flexibility is today where the concept of quality was 20 years ago” [Saleh 2009]

Exploring Methods for Valuing Flexibility

Total Ownership Cost (TOC) Approach

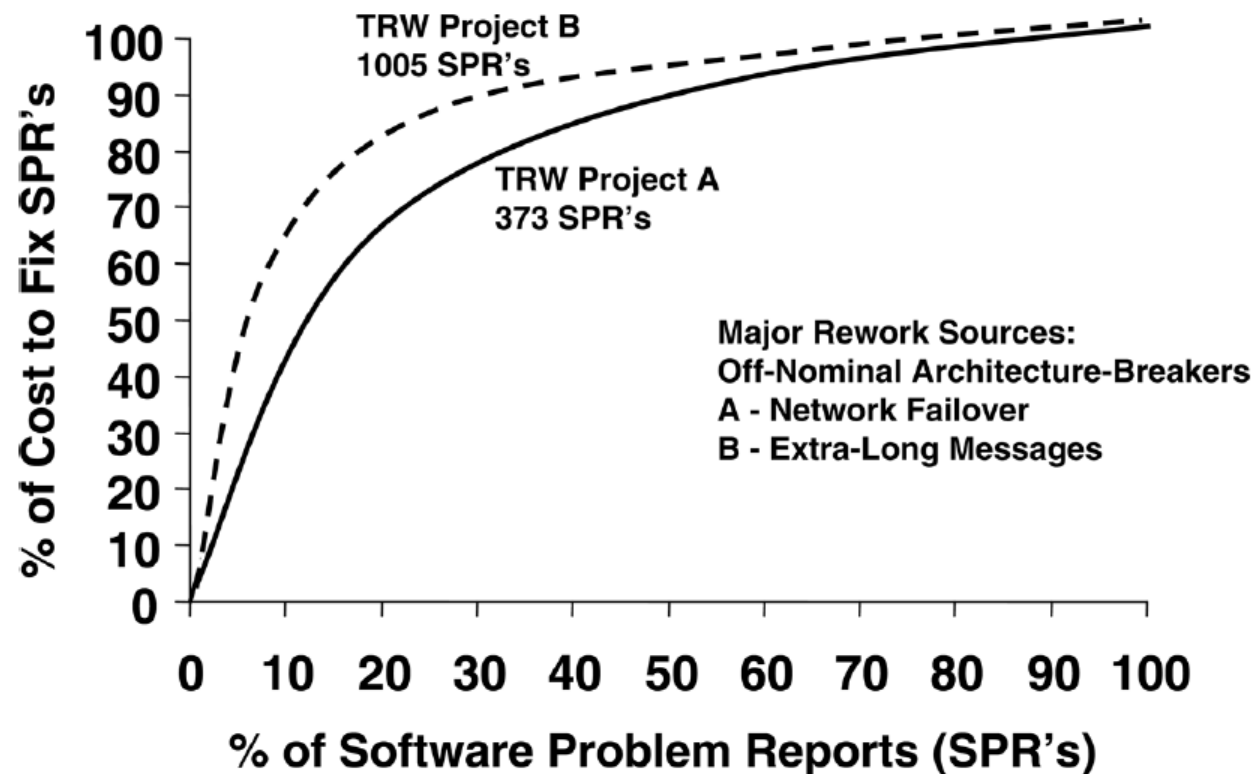
- **TOC Advantages, Challenges, Strategies**
 - Representative examples
- **TOC Analysis for Foreseeable Change**
 - Model and tool for individual systems
 - Calibrated to TRW C4ISR software data (3 systems)
 - Exploring calibration to NPS SHIPMAIN hardware data
 - Model and tool for families of systems
 - Calibrated to COCOMO II software data (161 projects)
 - Exploring calibration to AFIT modular munitions hardware data
- **Candidate Extensions**
 - Refined and extended model capabilities
 - Particular domains, tradeoff analyses, enterprise analysis
 - Effects of adaptation to unforeseeable change
 - Integration with alternative valuation models

TOC Advantages, Challenges, Strategies

- **TOC Advantages**
 - Increasingly required (DoDI 5000.02, WSARA 2009)
 - Easy to understand across specialty domains
 - Clear cause-effect relationships, straightforward calibration
- **TOC Challenges**
 - Defining flexibility investment costs, resulting cost reductions
 - Rework and change-adaptation cost reductions a proxy for benefits
 - Predicting uncertain futures
- **TOC Approach Strategies**
 - Tailor analysis approaches to common situations
 - DoDI 5000.02 milestone reviews, make-or-buy decisions
 - Explicitly emphasize need to define evolution requirements
 - Not just snapshot capability, interface, KPP, project requirements
 - Start with simple models and tools, refine and extend as needed

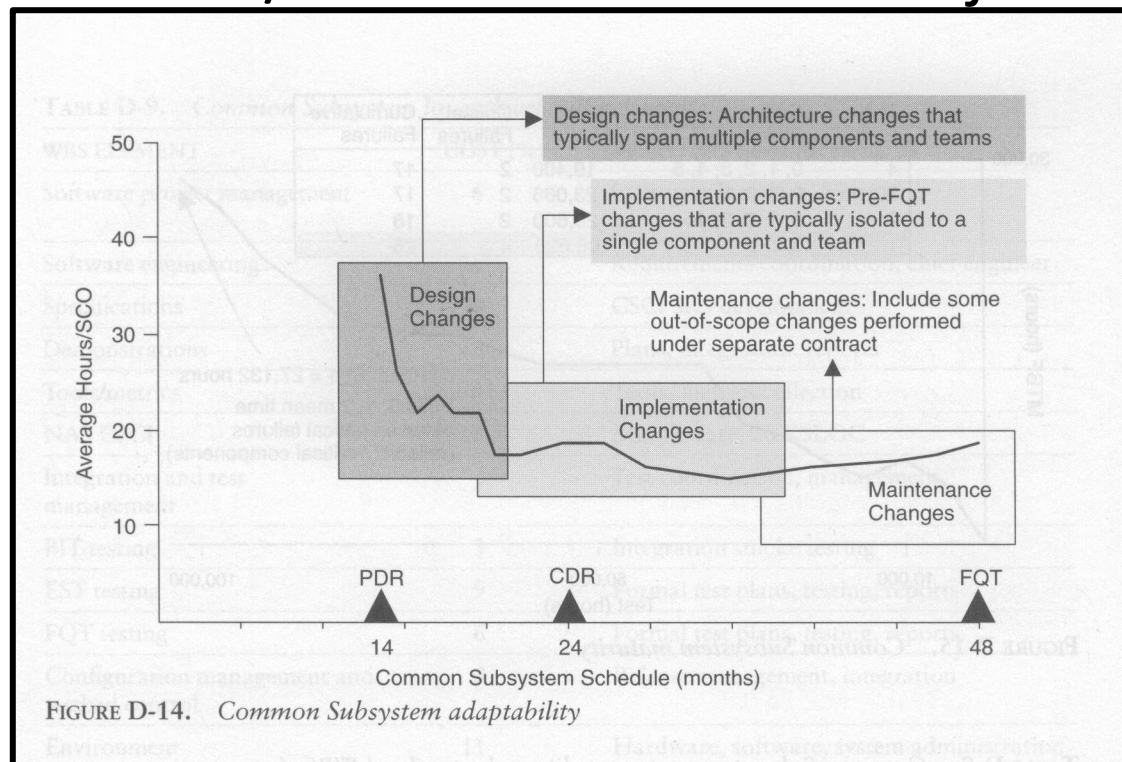
Point-Solution Architectures Cause Major Rework

C4ISR Contracts: Nominal-case requirements; 90 days to PDR



C4ISR Project C: Architecting for Change

USAF/ESC-TRW CCPDS-R Project*



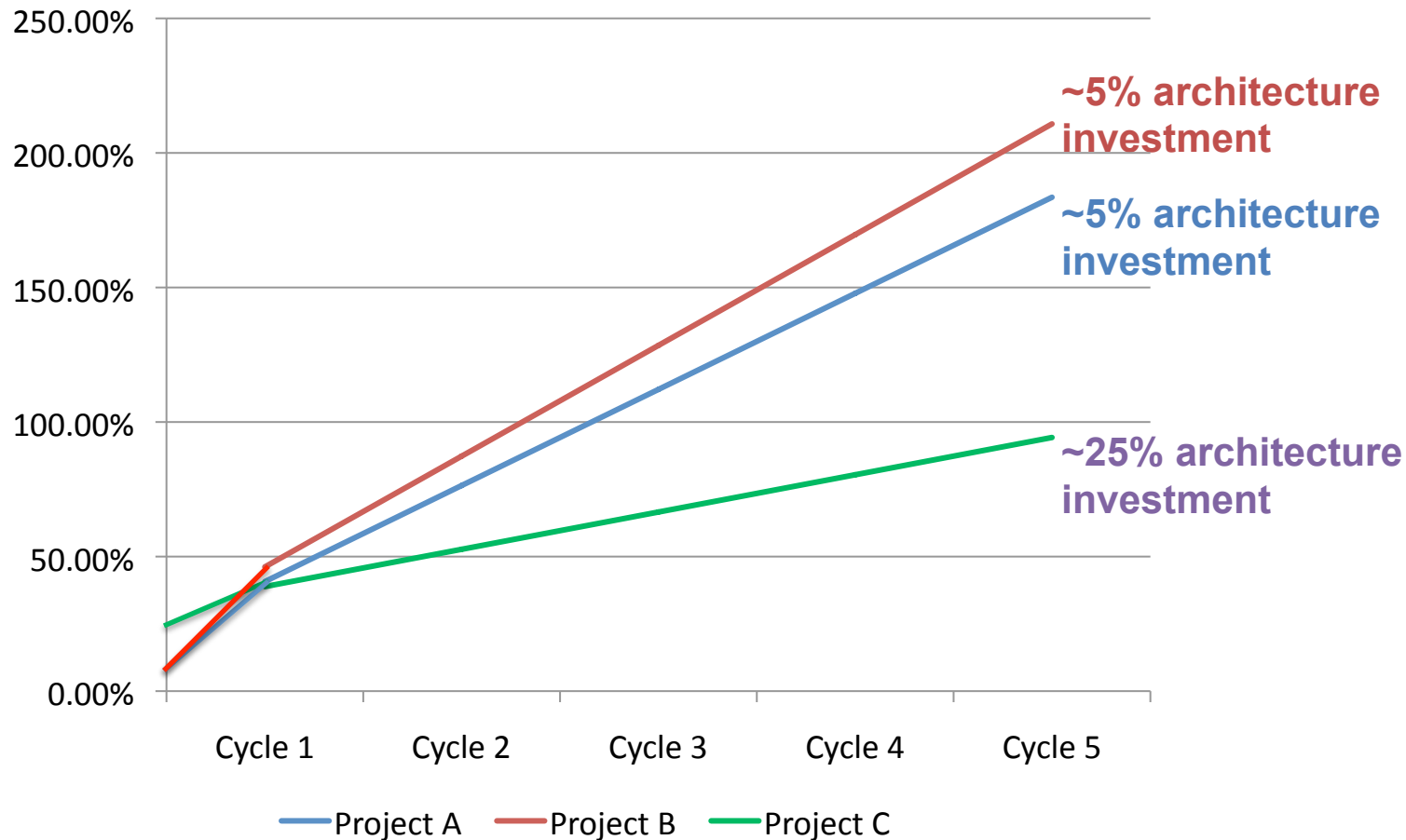
***When investments made in architecture,
average time for change order becomes
relatively stable over time...***

* Walker Royce, *Software Project Management: A Unified Framework*. Addison-Wesley, 1998.

Single-System TOC Model Example

	A	B	C	D	E
1	Input Parameters	System			
2		A	B	C	
3	Software Size (KSLOC)	100	100	355	
4	# Change Requests/Release	373	1005	1600	
5	# Change Requests (I&T only)				
6	# I&T Change Requests/Release/ > 1 PM	27	22		
7	# Total Change Requests/Release/ > 1 PM			16	
8	Change Request Fix Time (See assumption #2)	261	356	263	
9	Total Effort (Person Months)	731	865	1900	
10	% Arch, RESL	5%	5%	25%	
11	% Rework, RVOL	35.70%	41.16%	13.85%	
12					
13	Cumulative Total Cost of Ownership	Project A	Project B	Project C	
14	Cycle 1	40.70%	46.16%	38.85%	
15	Cycle 2	76.41%	87.31%	52.70%	
16	Cycle 3	112.11%	128.47%	66.55%	
17	Cycle 4	147.82%	169.62%	80.40%	
18	Cycle 5	183.52%	210.78%	94.25%	

Relative* Total Ownership Cost (TOC)

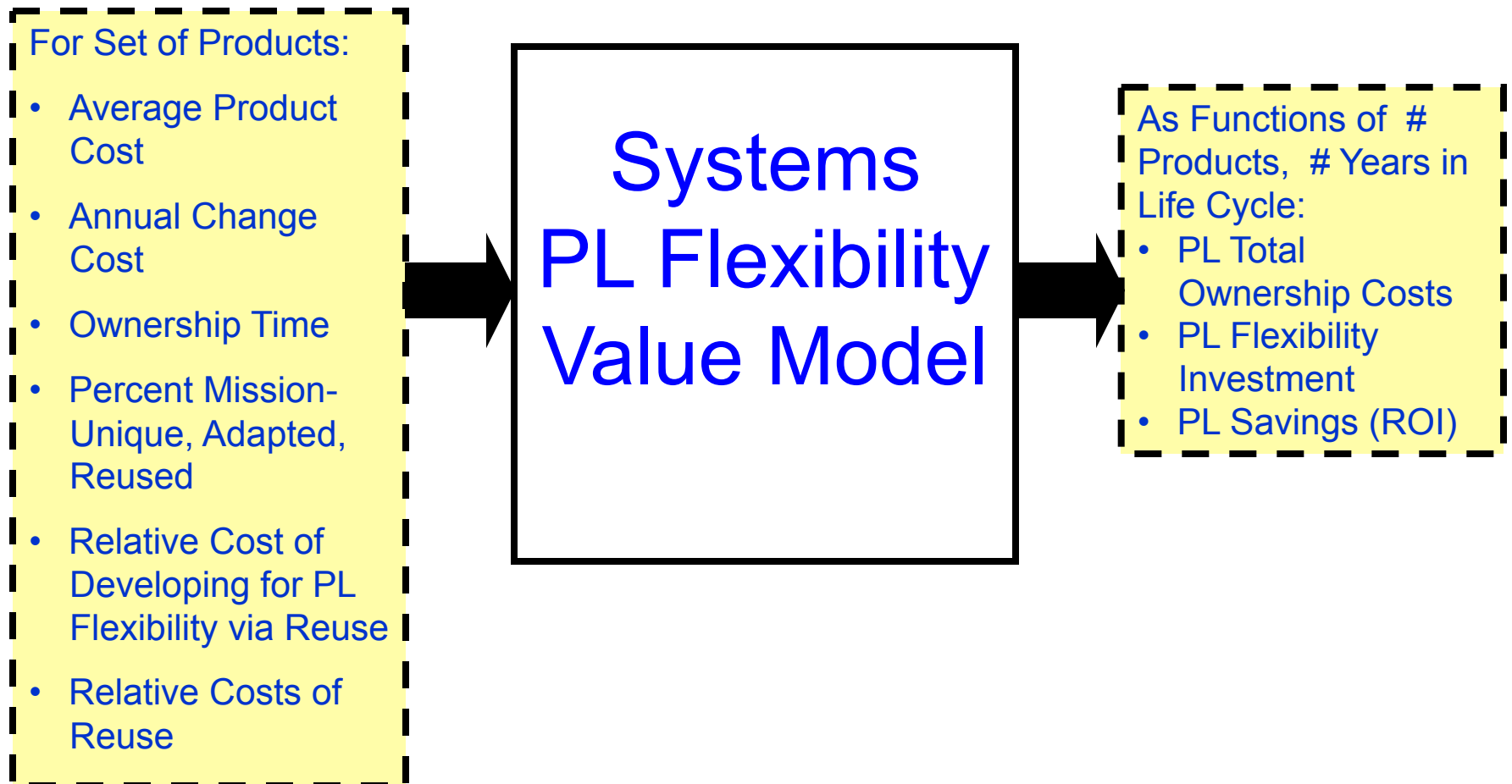


* Cumulative architecting and rework effort relative to initial development effort

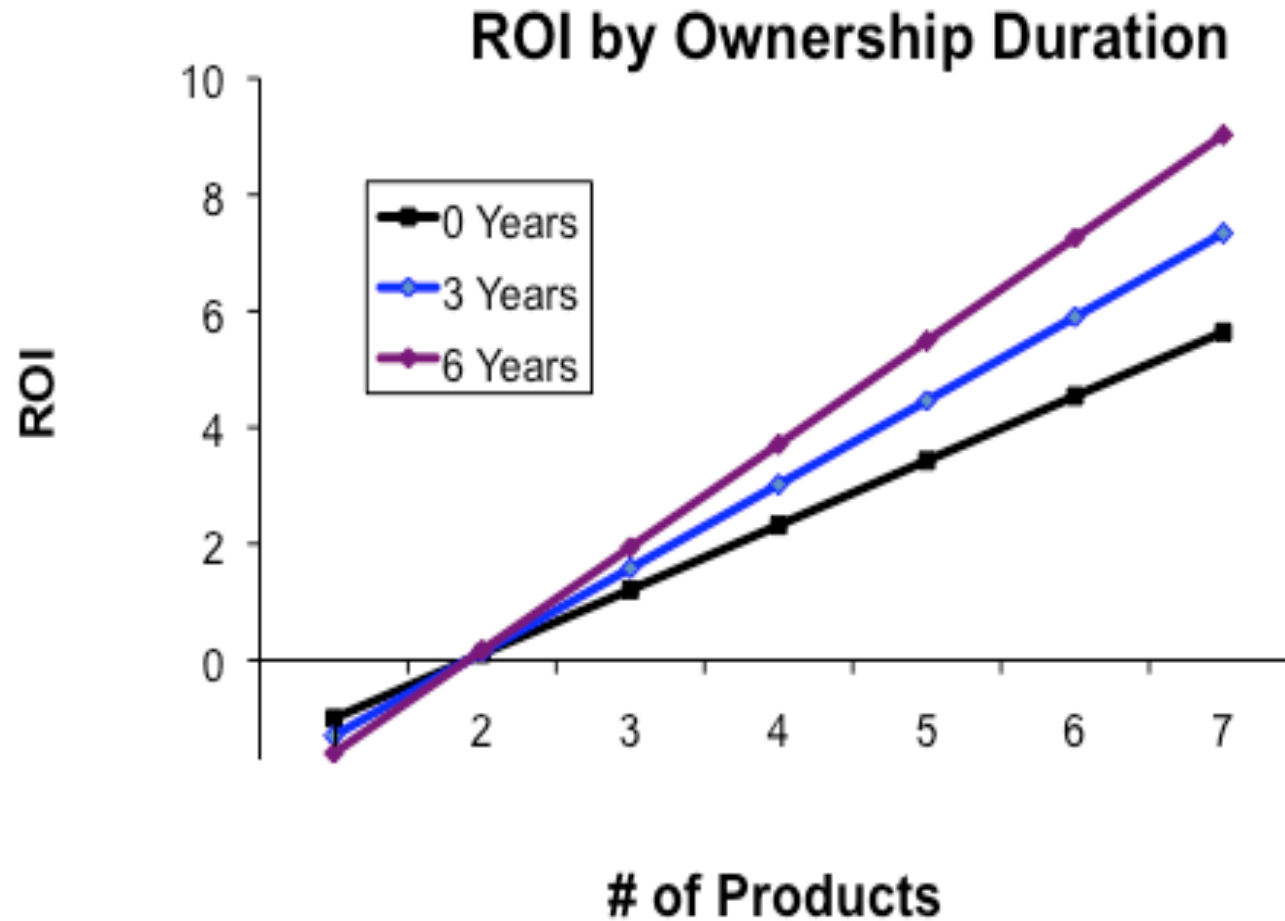
Example of Use: MS A Preparation Guidance

- Alternatives analyzed shall include at least one architecture organized around:
 - Common sources of life-cycle change
 - For RPVs, these usually include user interface displays and controls, new payloads, self-defense and electronic warfare, data fusion, NCSoS protocols, and hardware maintainability
 - Risk analysis and prototyping of critical off-nominal scenarios
 - For RPVs, these usually include communications outages, anti-RPV threats, noisy and intermittent data sources, redirected missions, and cross-RPV coordination of responses
- Analyses of alternatives shall include total ownership cost comparisons
 - Based on relevantly-calibrated life cycle cost models

Systems Product Line Flexibility Value Model



Sensitivity Analysis Example



Conclusions and Candidate Extensions

- **TOC approach has several advantages**
 - Increasingly required (DoDI 5000.02, WSARA 2009)
 - Easy to understand across specialty domains
 - Clear cause-effect relationships, straightforward calibration
- **Important to determine evolution requirements**
- **Basic models available for foreseeable change**
 - Can be used to support TOC-based milestone decisions
 - Individual systems, families of systems
 - Best to have calibration data
- **Candidate Extensions**
 - Refined and extended model capabilities
 - Particular domains, tradeoff analyses, enterprise analysis
 - Integration with alternative valuation models

Projects A and B Major Rework Sources

- Change processing over 1 person-month = 152 person-hours

Category	Project A	Project B
Extra long messages		$3404+626+443+328+244= 5045$
Network failover	$2050+470+360+160= 3040$	
Hardware-software interface	$620+200= 820$	$1629+513+289+232+166= 2832$
Encryption algorithms		$1247+368= 1615$
Subcontractor interface	$1100+760+200= 2060$	
GUI revision	$980+730+420+240+180 =2550$	
Data compression algorithm		910
External applications interface	$770+330+200+160= 1460$	
COTS upgrades	$540+380+190= 1110$	$741+302+221+197= 1461$
Database restructure	$690+480+310+210+170= 1860$	
Routing algorithms		$494+198= 692$
Diagnostic aids	360	$477+318+184= 979$
TOTAL:	13620	13531

Real Options/Knowledge Value Added

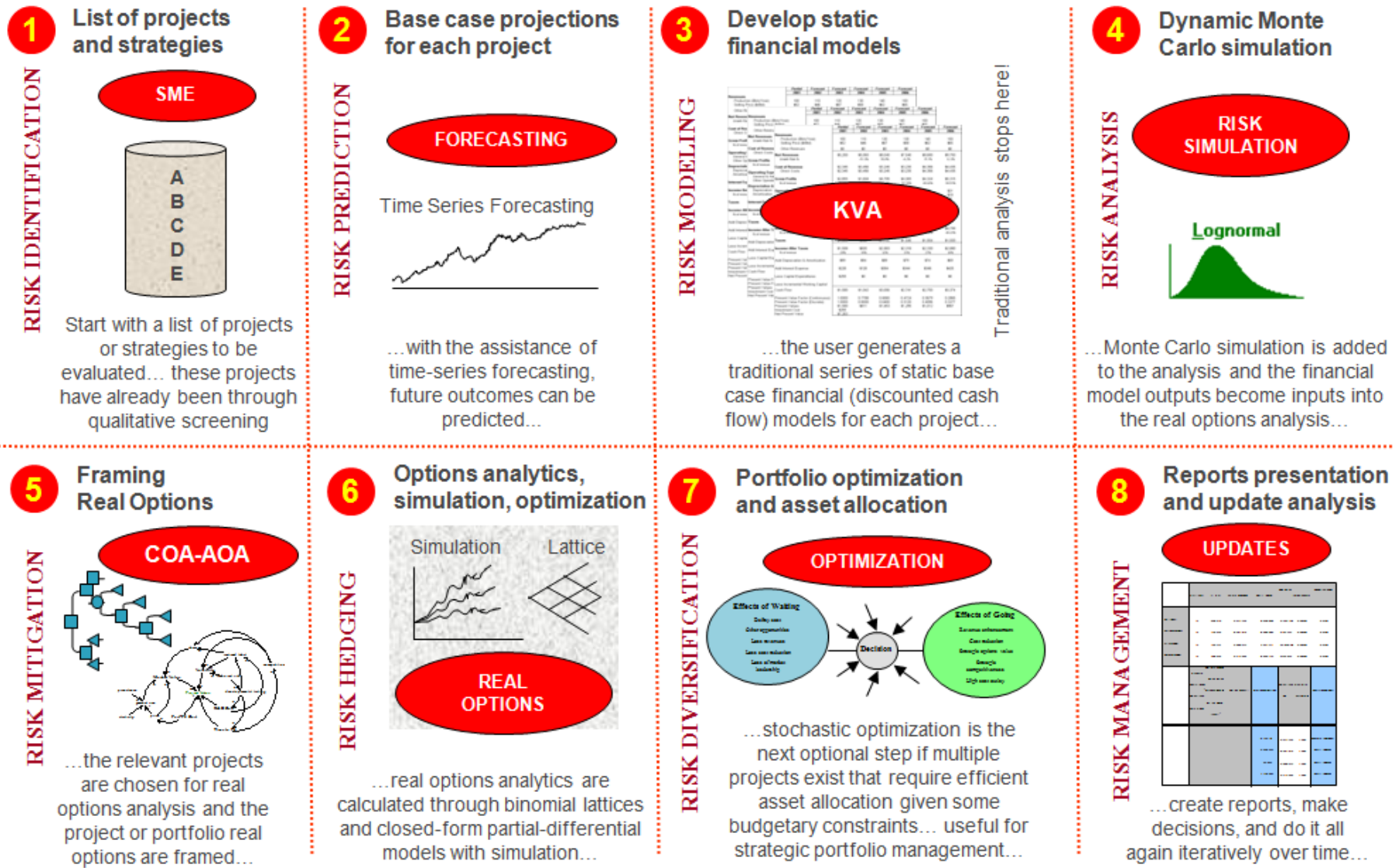
KVA+RO+IRM are a combination of method and toolsets to assist the executive in decision making

- Knowledge Value Added (KVA) is a method that systematically expresses non-revenue activities in common units of output to quantify value
- Real Options (RO) provides a way to qualitatively and quantitatively evaluate the relative value of various courses of action under consideration
- Integrated Risk Management combines KVA and RO with a powerful toolset to assist the program manager in the decision process
- Treatment of parameters as distributions permits rigorous analysis in an uncertain world, where instead of single point estimates, we use ranges as inputs
- Monte Carlo risk simulation and process models permit consideration of possible outcomes within a reasonable time period
- Disciplined processes yield defensible results that can be updated as more knowledge/ information is realized by the program
- Risk simulation, sensitivity analysis, and forecasting are automated (analyses are efficient, quick, consistent, replicable, defensible, and scalable)

Measuring Value

- KVA **quantifies the value** of the knowledge used to produce common units of output
- Shows decision makers the **benefit and cost** of each program or project
- Measures how resources are allocated in terms of the volatility of productivity (e.g., ROI)
- **Providing ROI volatility inputs to IRM**
- **Military value** in this study was postulated to be represented by capability provided to the warfighter measured in a variety of ways
 - Strategic importance as represented by OPNAV sponsor priorities
 - Technical value as represented by acquisition community priority
 - Functional complexity represented by Delivered Source Lines of Code (DSLOC)
 - Subject Matter Expert evaluation of complexity and mission criticality, aggregated from the component level

Integrated Risk Management(IRM)



The IRM toolset provides powerful tools for analyzing the data

- Treatment of parameters as distributions permits rigorous analysis in an uncertain world
- Instead of single point estimates, we use ranges as inputs
- Monte Carlo simulation and process models permit consideration of all possible outcomes within a reasonable time period
- Disciplined processes yield defensible results that can be updated as more knowledge/ information is realized by the program
- Risk simulation, sensitivity analysis, and forecasting are automated (analyses are efficient, consistent, replicable, defensible, and scalable)

AEGIS Case: Introduction and Context

- **Introduction of Open Architecture (OA) business and technical processes provides opportunity to improve acquisition**
 - Increased competition
 - Shorter cycle time
 - Reduced total ownership and acquisition cost
- **The AEGIS Advanced Capability Build (ACB) process is one implementation of the OA approach**

The ACB Process

- The ACB process provides for software updates to ships within the program on a two-year cycle
- ACBs are identified by the first year in which they will be fielded, e.g., ACB-14
- US Navy CGs and DDGs will be inducted into the process as they receive computing plant updates during major availabilities that convert the processors and networks to a COTS-based configuration
- The hardware baseline that supports OA must be in place to begin execution of the ACB process
- Once a ship is inducted, it will receive the scheduled update plus any previous updates (e.g., ACB 16 ships entering the program will receive ACB 14 capabilities as well)

The problem addressed in this study deals with risk and value

- Value is realized through fielding of military capability for the war-fighter
- Risk is found in uncertainty
 - Cost uncertainty creates budget risk
 - Technology risk can lead to schedule and budget risk
- This study provided a pilot implementation of the Knowledge Value Added + Integrated Risk Management method to represent value and risk to assist the PM and sponsor in selecting the proper capability mix to field in a given ACB
- The problem space considered 23 capabilities to be implemented through changes to 32 software components across three scheduled ACBs (ACB 14, 16, and 18)
- Given the universe of desired capabilities, the problem is to select those providing the best value to the war-fighter for inclusion in a given ACB subject to budget constraints, risk and uncertainty of cost and timing

The study articulated a notional value of military value and used powerful financial and analytical tools

- Knowledge Value Added (KVA) provides ways of representing outputs (value) in common units
- Real Options provides tools to compare the value stream of various options in rigorous terms
- Integrated Risk Management considers uncertainties and represents risk in quantitative, clear and defensible terms

Model input assumptions are entered on a data sheet

Common sizing inputs and using weights to obtain the expected military value

			Common Size Factor																	
			1.00			0.10			2.00			2.00								
			35%			35%			15%			15%								
			Weighting Scheme																	
			High	Mid	Low	SME Mean Value Added	Technical Priority	OPNAV Priority	DSLOC Complexity	Cost Simulation	Technical Priority H-L	OPNAV Priority H-L	EMV Score	EMV Score	EMV Score	Objective Used	CV			
Capability																				
Capability 1						43.00	3	2	278	29.00	21	22	321.00	37.68	43.00	43.00	0.1834			
Capability 2						28.00	2	1	541	126.00	22	23	569.00	42.24	45.00	45.00	0.0903			
Capability 3						13.00	1	3	58	77.00	23	21	71.00	19.78	44.00	44.00	0.0719			
Capability 4						40.33	5	4	635	21.00	19	20	675.33	48.04	39.00	39.00	0.0576			
Capability 5						17.67	7	7	134	15.00	17	17	151.67	21.07	34.00	34.00	0.0407			
Capability 6						35.67	4	6	392	27.00	20	18	427.67	37.60	38.00	38.00	0.1568			
Capability 7						50.67	6	5	549	17.00	18	19	599.67	48.05	37.00	37.00	0.0481			
Capability 8						47.67	10	11	675	77.00	14	13	722.67	48.41	27.00	27.00	0.0689			
Capability 9						19.00	8	8	109	16.00	16	16	128.00	20.07	32.00	32.00	0.0382			
Capability 10						33.67	11	9	189	10.00	13	15	222.67	26.80	28.00	28.00	0.0603			
Capability 11						20.00	9	10	88	3.00	15	14	108.00	18.78	29.00	29.00	0.0707			
Capability 12						27.67	14	12	159	21.00	10	12	186.67	21.85	22.00	22.00	0.1137			
Capability 13						27.67	12	13	159	11.00	12	11	186.67	22.15	23.00	23.00	0.0408			
Capability 14						44.67	13	14	523	27.00	11	10	567.67	40.24	21.00	21.00	0.0956			
Capability 15						17.67	20	15	134	10.00	4	9	151.67	14.77	13.00	13.00	0.0603			
Capability 16						17.67	21	16	134	5.00	3	8	151.67	14.17	11.00	11.00	0.0816			
Capability 17						34.33	19	17	328	9.00	5	7	362.33	27.10	12.00	12.00	0.0454			
Capability 18						17.67	22	18	134	6.00	2	6	151.67	13.27	8.00	8.00	0.0372			
Capability 19						14.00	23	19	81	18.00	1	5	95.00	9.54	6.00	6.00	0.0340			
Capability 20						17.67	15	20	134	14.00	9	4	151.67	14.77	13.00	13.00	0.0164			
Capability 21						22.67	18	21	144	18.00	6	3	166.67	15.67	9.00	9.00	0.0454			
Capability 22						11.67	16	22	180	78.00	8	2	191.67	13.38	10.00	10.00	0.0468			
Capability 23						10.00	17	23	95	10.00	7	1	105.00	9.23	8.00	8.00	0.0603			

Starting with 23 capabilities (more to be added later when there is sufficient data)

High, most likely, low cost estimates for running thousands of simulation trials

Technical and OPNAV priorities

DSLOC provides a measure of complexity

Intermediate computations: risk-simulation assumption, readjusted priorities, expected military score and cost-based risk coefficients

Running the model provides recommended selections

ACB 14 sample results with \$150M budget constraint

Expected Military Value: SME Mean Value Added, DSLOC Complexity, Common Sized, Weighted OPNAV/Technical Priorities

Selection of EMV calculation method

Capability	Reset	EMV	Cost	Risk \$	Risk %	Selection
Capability	Actual Capabilities Redacted	37.68	Cost Data Redacted	\$6.91	18.34%	0.0000
Capability 1		42.24		\$3.81	9.03%	0.0000
Capability 2		19.78		\$1.42	7.19%	0.0000
Capability 3		48.04		\$2.77	5.76%	1.0000
Capability 4		21.07		\$0.86	4.07%	1.0000
Capability 5		37.60		\$5.90	15.68%	0.0000
Capability 6		48.05		\$2.31	4.81%	1.0000
Capability 7		48.41		\$3.34	6.89%	0.0000
Capability 8		20.07		\$0.77	3.82%	1.0000
Capability 9		26.80		\$1.62	6.03%	1.0000
Capability 10		18.78		\$1.33	7.07%	1.0000
Capability 11		21.85		\$2.48	11.37%	0.0000
Capability 12		22.15		\$0.90	4.08%	1.0000
Capability 13		40.24		\$3.85	9.56%	1.0000
Capability 14		14.77		\$0.89	6.03%	1.0000
Capability 15		14.17		\$1.16	8.16%	1.0000
Capability 16		27.10		\$1.23	4.54%	1.0000
Capability 17		13.27		\$0.49	3.72%	1.0000
Capability 18		9.54		\$0.32	3.40%	0.0000
Capability 19		14.77		\$0.24	1.64%	0.0000
Capability 20		15.67		\$0.71	4.54%	0.0000
Capability 21		13.38		\$0.63	4.68%	0.0000
Capability 22		9.23		\$0.56	6.03%	0.0000
Capability 23						

Go or No-Go decisions in the portfolio selection

Benefits (EMV), Cost, Risk are considered

Max EMV

Total Constraints:

314.51	\$150.00	\$6.18
MAX	\$150.00	

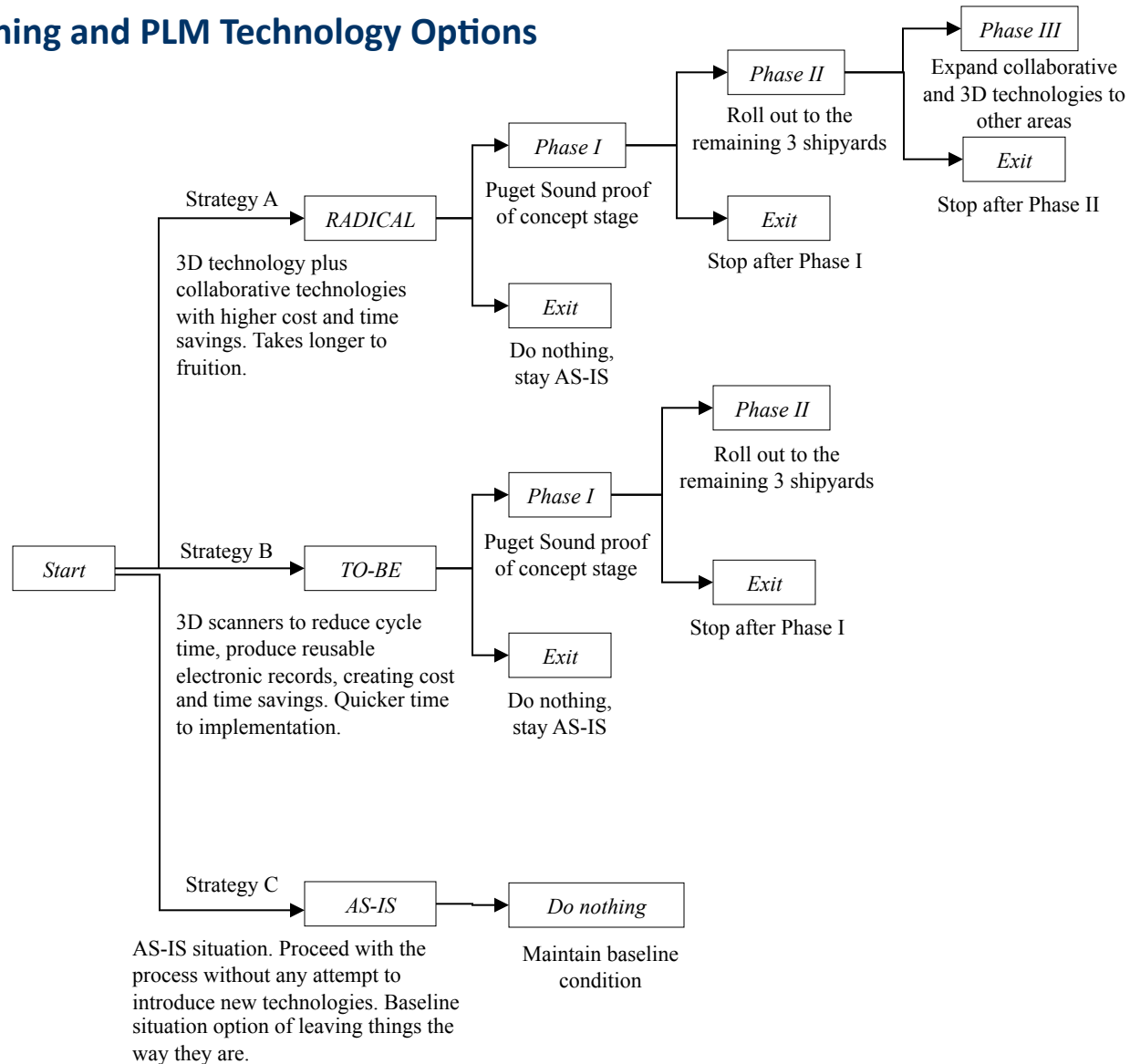
Constraints can be set (budget, capability count, FTE, priorities, etc)

Starting with 23 capabilities (more to be added later when there is sufficient data)

SHIPYARD PLANNING PROCESS (MODERNIZATION AND MAINTENANCE)

- The DoD spends more than \$59 billion/year on a broad range of defense maintenance capabilities and programs.
- Current inventory of 300 ships, 15,000 aircraft, 900 strategic missiles, and 330,000 ground vehicles, the need for maintenance programs is evident.
- Navy Fleet maintenance and modernization efforts for fiscal year 2005 amounted to 85 ship and submarine scheduled availabilities cost \$3.9 billion (Hugel, 2005).
- The Navy must be extremely diligent in its maintenance efforts. Ships and submarines provide great value to national defense objectives. Maintenance and modernization policy is carefully designed to keep Navy ships operating at the maximum level of material readiness possible (OPNAVINST 4700.7K).
- This project looked at the business process for conducting industrial work in Naval Shipyards and the effect that deploying an imaging technology could have

3D Scanning and PLM Technology Options



We can quantify real options analysis values/results

Maturity (Years)	5
Risk-Free Rate (%)	5.00%

Strategic Option Valuation

	AS-IS	TO-BE	RADICAL
Benefits	\$ 49,175,536.83	\$ 93,344,192.00	\$ 95,097,452.00
Costs	\$ 44,705,033.48	\$ 7,854,206.09	\$ 4,488,887.70
Volatility	N/A	8.04%	9.81%
Total Strategic Value	\$ 4,470,503.35	\$ 87,227,330.00	\$ 91,601,502.00
Factor Increase		19.51	20.49

Expansion Valuation on Stage-Gate Options

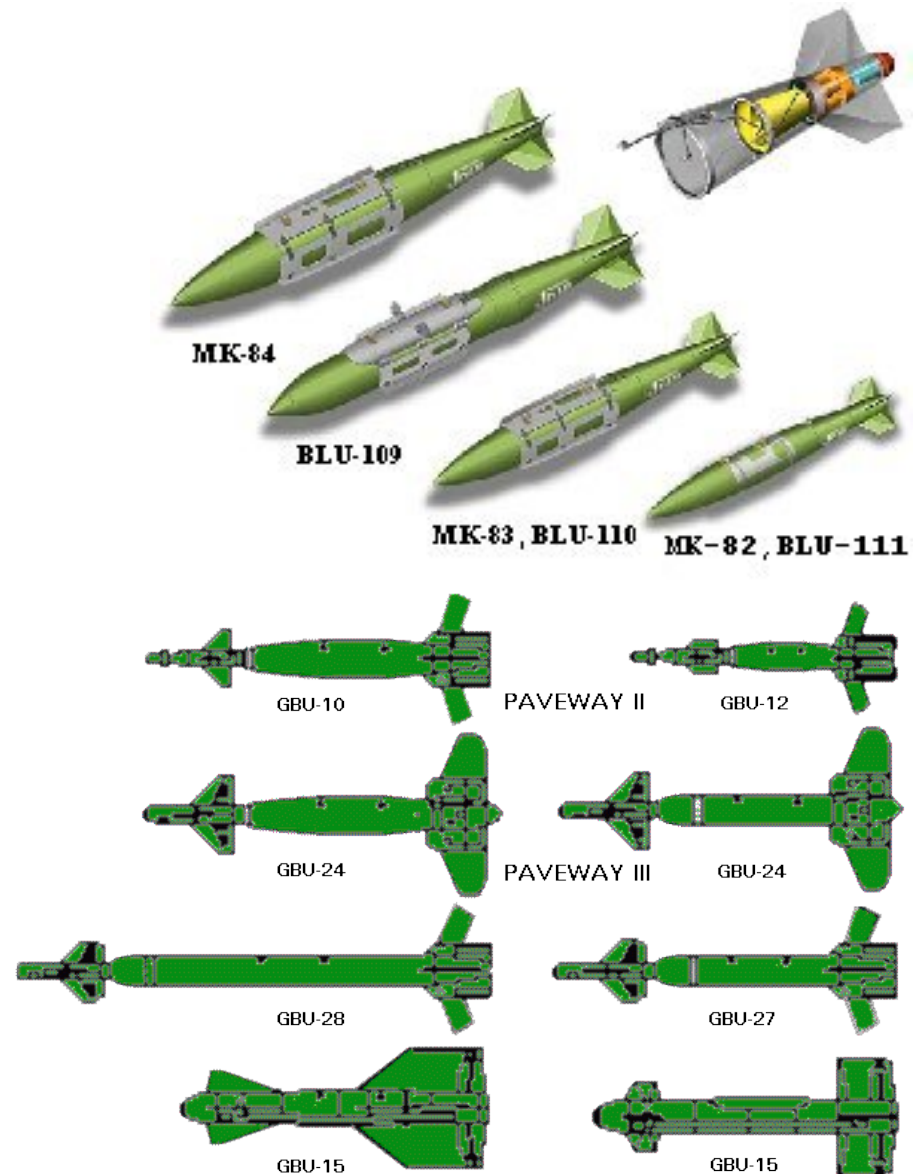
Maturity (Years)	10	10	10
Factor Increase	3	3	10

	AS-IS	TO-BE	RADICAL
Benefits	\$ 147,526,610.48	\$ 280,032,576.00	\$ 950,974,520.00
Costs	\$ 134,115,100.43	\$ 23,562,618.26	\$ 44,888,876.96
Volatility	N/A	25.43%	31.02%
Long Term Total Strategic Value	\$ 13,411,510.04	\$ 265,742,275.00	\$ 923,752,800.00
Factor Increase		19.81	68.88

Common Use Case Study

Initial Case Study Modular Munitions

- DoD uses modular munitions to achieve operational flexibility
- Various configurations are allowable based on warhead, fuze and guidance module selection
- Munitions are assembled in the field according to the days Air Tasking Order



Relating Functionality to Capability

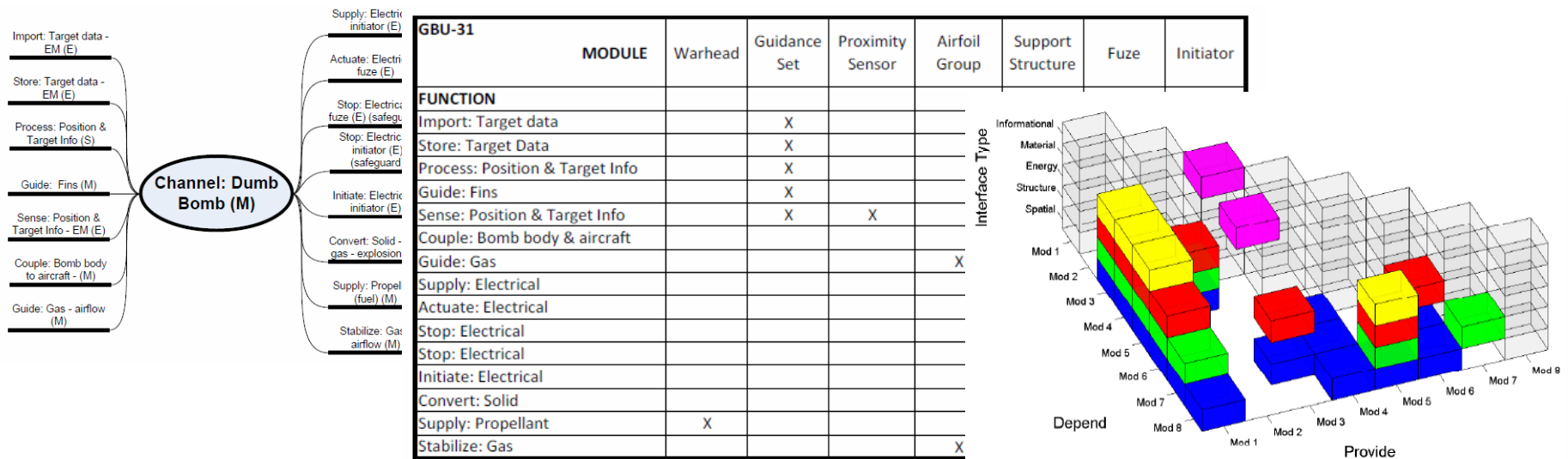
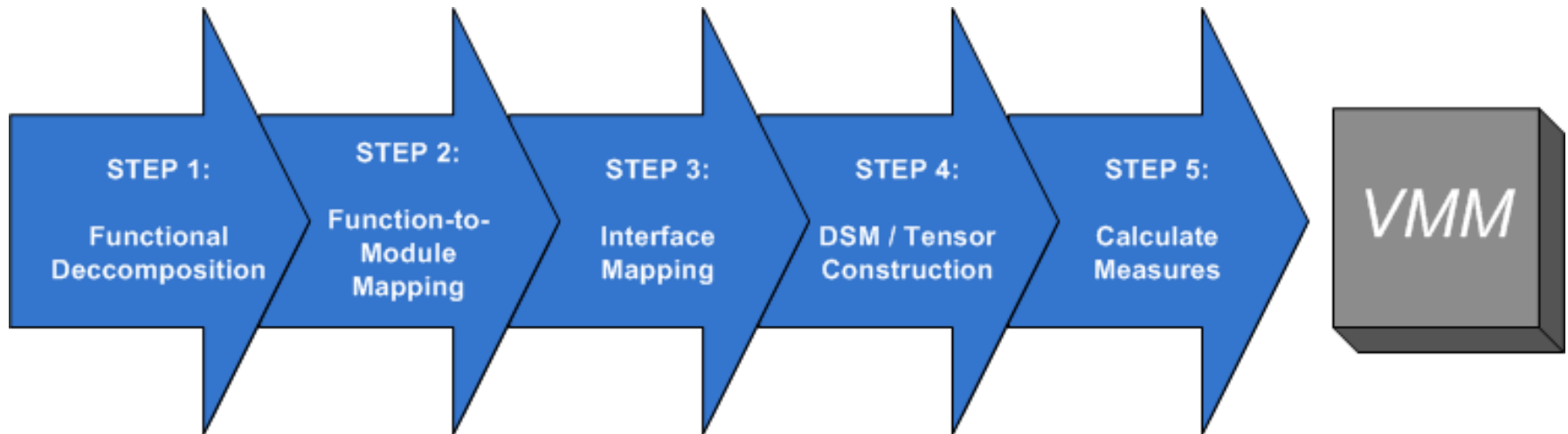
- Candidate tasks from UJTL
 - OP 3.2 Attack Operational Targets**
 - OP 3.2.1 Provide Close Air Support Integration for Surface Forces**
 - OP 3.2.2 Conduct Non-Lethal Attack**
 - OP 3.2.4 Suppress Enemy Air Defenses**
 - OP 3.2.5 Interdict Operational Forces/Targets**
 - OP 3.2.5.2 Conduct Surface/Subsurface Firepower Interdiction of Operational Forces/Targets**
 - OP 3.2.6 Provide Firepower in Support of Operational Maneuver**
- Additional task definition is necessary
 - OP 3.X.X Defeat fixed surface targets**
 - OP 3.X.X Defeat mobile surface targets**
 - OP 3.X.X Defeat sub-surface targets**
 - OP 3.X.X Defeat Area Targets**
 - OP 3.X.X Defeat Chem/Bio Facilities**
 - OP 3.X.X Limit Collateral Damage (possibly an attribute/measure of other tasks)**
 - OP 3.X.X Survive enemy air defenses**
- Existing and/or proposed system modifications can be measured against the capabilities defined by tasks such as these

Relating System Modifications to Expanded Capability

- “Bunker Buster” of Desert Storm (evolved into GBU-28)
 - New warhead “module” used in conjunction with existing guidance and fuze modules
 - Expanded capability for tasks:
 - OP 3.2.5.2 Conduct Surface/Subsurface Firepower Interdiction of Operational Forces/ Targets**
 - OP 3.X.X Defeat sub-surface targets**
- “Agent Defeat” munition concept
 - New warhead module – can be substituted for BLU-109
 - Expanded capability for task:
 - OP 3.X.X Defeat Chem/Bio Facilities**
- JDAM provided a new guidance option for existing warheads and fuzes
 - Expanded capability for task:
 - OP 3.X.X Survive enemy air defenses**
 - Expanded capability under degraded conditions for other tasks addressed by LGB
- Projected cost of achieving quantifiable additional capability can be assessed
 - At the “family of munitions” level, cost-benefit of modular design can be assessed based on both operational and programmatic flexibility

Flexibility in Design Feature Space

Assessing a Vector Modularity Measure* (VMM)



*Stryker, Jacques and Long; to appear in Journal of Engineering Design

Research Methodology

Vector Modularity Measure (VMM) Defined

$$VMM = \left[\begin{array}{ccc} 0-1 & 0-1 & 0-1^* \\ \frac{\sum_{i=1}^5 (\sum_{j=1}^n \sum_{k=1}^n DSM_{ijk})}{5n(n-1)} & \frac{n_{mp}}{n} & Y \\ V & X & Y \end{array} \right] \begin{array}{c} \\ \\ Z \end{array}$$

- Degree of Coupling, V
- Ratio of entries with an “x” to total entries across all five DSMs minus the diagonal entries
- 0 -1

	1	2	3	4	5	6	7	8	9	10
Element 1	1									
Element 2	x	2								
Element 3	x		3							
Element 4	x			4						
Element 5	x				5					
Element 6	x					6				
Element 7	x						7			
Element 8	x							8		
Element 9	x								9	
Element 10	x									10

- Reusability, X
- Ratio of modules used in multiple products (n_{mp}) to total number of modules in the product being analyzed (n)
- 0 -1

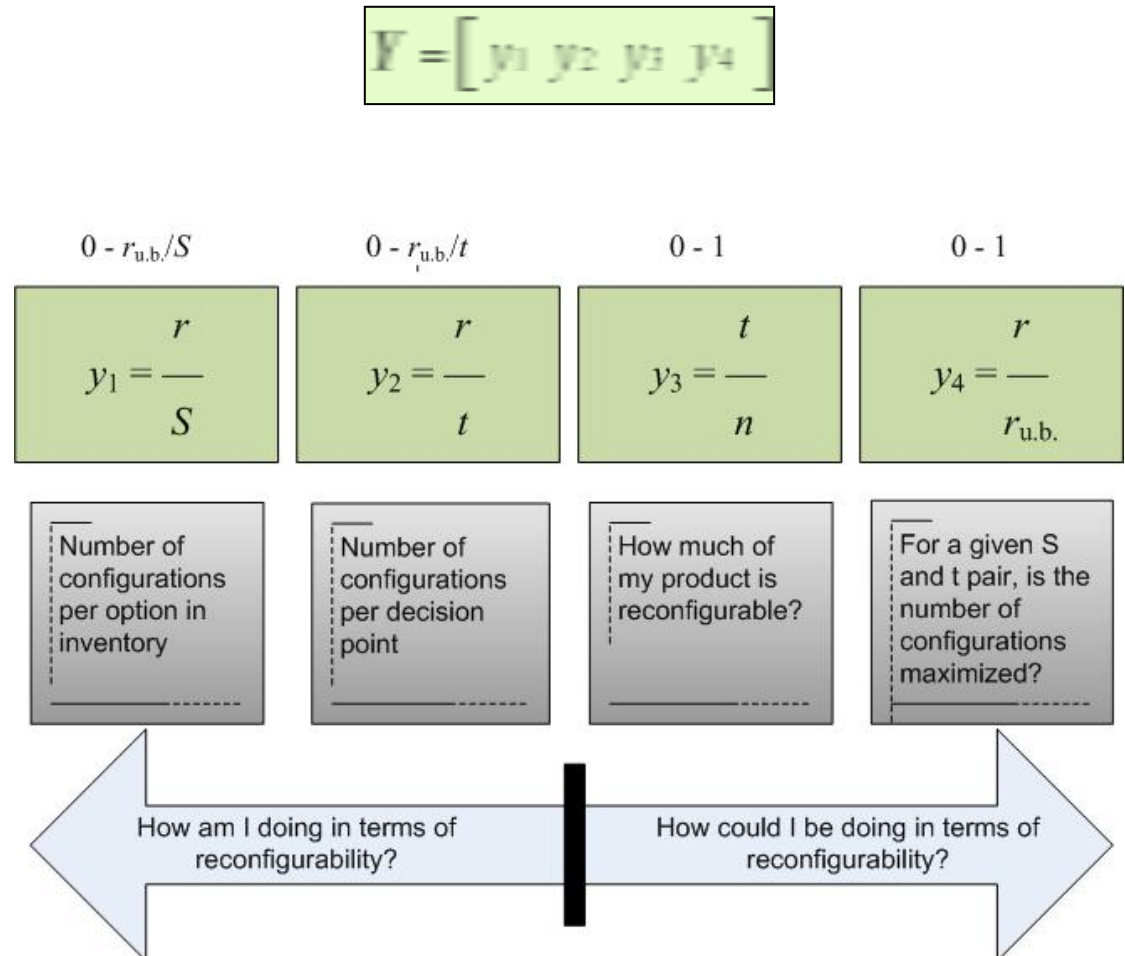
- Extensibility, Z
- Ratio of architectural options (a) to the total number of functions (m) performed by the product being analyzed
- Assumption: a product will not be fielded with less than 50% anticipated functionality
- 0 -1* (practical limit)

Research Methodology

Reconfigurability Measure Defined

Reconfigurability, Y	
n	Number of modules in a product
r	Number of possible reconfigurations
t	Number of modules with options
S	Total number of module options
$r_{u.b.}$	Upper bound number of reconfigurations for a given S and t pair

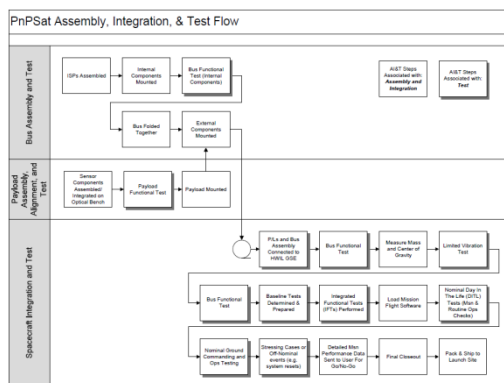
given S and t pair



Relating Modularity to Flexibility*

Modularity vs. A&CO

- Associating degree of coupling and assembly & checkout
 - Identify assembly and checkout procedures
 - Associate clock times with each step
 - Identify required modules to perform each step and associated interface types
 - Summarize clock times associated with handling each module and associated interface types



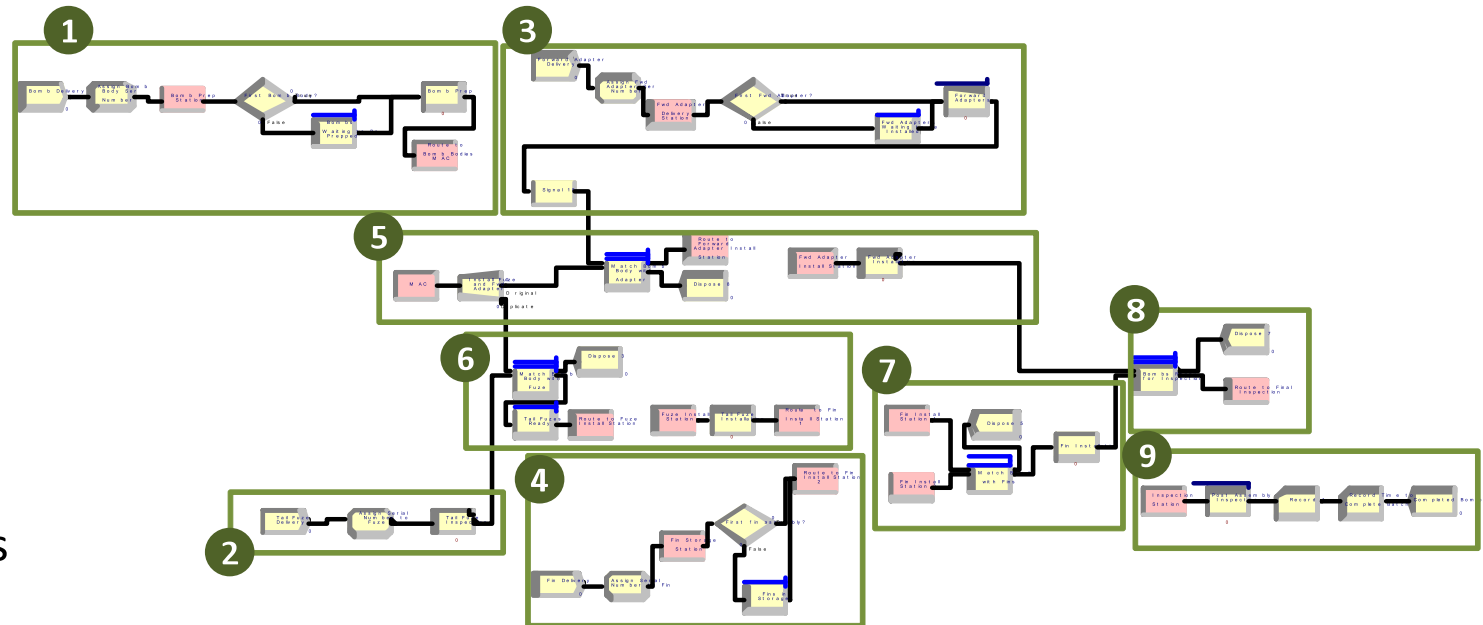
Step	Description	Duration (hours)
1	Assembly of the bus structure in a "flat-satellite" configuration	1.37 ^a
2	Install the internal components and mate harnesses to the power and data network	1.37 ^a
3	Power up the vehicle on internal power and run a bus functional test to verify internal devices	0.83
4	Fold up the bus panels and install external components, including solar array	1.48
5	Install payload items	3.0 ^b
6	Connect the RF links from the vehicle to the ground station	0.25
7	Power-up the vehicle with solar array simulator power and run bus functional test	1.28
8	Lift and measure vehicle mass and center of gravity	0.98
9	Place on vibration table and run sine sweeps and single axis random vibration (Optional)	1.17 ^c
10	Power-up and run bus functional test	0.83 ^d
11	Demonstrate S-Band and UHF Compatibility to ground station simulator	0.33
12	Demonstrate array first-motion deployment	0.08
13	Deploy array and illuminate to verify end-to-end power flow	0.17
14	Load Mission Flight Software	0.25
15	Run nominal Day in the Life scenario and verify L/E/O events	3.0 ^e
16	Perform nominal ground commanding and ops testing with RF links	3.0 ^f
17	Perform stressing cases or off-nominal events (device POR, system resets)	3.0 ^f
18	Set vehicle for launch	1.5 ^f

		Modules								Interfaces					
Step	Description	STRUC	P/L	PWR	THRM	TEL	AV	ADCS	LV	RF	I	M	R	FT	
1	Assembly of the bus structure in a "flat-satellite" configuration	X								X				X	
2	Install the internal components and mate harnesses to the power and data network	X		X			X	X	X	X					
3	Power up the vehicle on internal power and run a bus functional test to verify internal devices			X			X	X	X		X		X		
4	Fold up the bus panels and install external components, including solar array	X		X	X	X	X		X	X				X	
5	Install payload items	X	X							X				X	
6	Connect the RF links from the vehicle to the ground station	X					X	X			X				
7	Power-up the vehicle with solar array simulator power and run bus functional test		X	X	X	X	X	X	X		X		X		
8	Lift and measure vehicle mass and center of gravity	X	X	X	X	X	X	X	X					X	
9	Place on vibration table and run sine sweeps and single axis random vibration (Optional)	X	X	X	X	X	X	X	X					X	
10	Power-up and run bus functional		X	X	X	X	X	X	X		X		X		
11	Demonstrate S-Band and UHF Compatibility to ground station simulator						X	X		X					
12	Demonstrate array first-motion deployment	X		X						X		X	X	X	

Relating Modularity to Flexibility

Simulation Model

- Developed in Arena™
- Two basic models (GBU-24, GBU-31)
- Input data collected from Air Force SMEs
- Modified models to test effects of alternate designs / architectures on assembly and checkout times



1. Bomb Body Preparation
2. Fuze Preparation
3. Forward Adapter Queuing
4. Fin Queuing
5. Forward Adapter Installation
6. Fuze Installation
7. Fin Installation
8. Fully Assembled
9. Final Inspection

GBU-24 Assembly & Checkout Model

Other Case Studies

PnPSat

$$VMM_{PnPSat} = \begin{bmatrix} 0.27 & 0.88 & Y_{PnPSat} & 0.92 \end{bmatrix}$$

$$Y_{PnPSat} = \begin{bmatrix} 6 & 18 & 0.5 & 0.89 \end{bmatrix}$$

- Used to evaluate current design and make recommendations to further increase modularity
- Modularity benefits being realized the most: Reusability and Extensibility
- Close to maximizing number of reconfigurations possible for S and t pair

• Recommendations:

- Increase options for the spacecraft bus module
- Add “scars” for a future propulsion capability (function)
- Determine options for each module; module options used in the assessment are “planned” modules and are not yet in inventory



Gaps, Plans and Priorities

Gap: What's out there? Will it work, here?

The open literature:

- Almost all treatment of flexibility appears in the Engineering Design literature and Software Engineering literature.
- There is no widely accepted definition of flexibility ... often synonymous with other "...ilities."
- Almost none of this literature directly addresses the value of flexibility.

Observation: There exist no general off-the-shelf modeling/analysis for evaluating the value of flexibility.

Gap: What's out there? Will it work, here?

Generic modeling/analysis:

- Simulation.
- Net Present Value Analysis (e.g., Total Cost of Ownership).
- Portfolio Theory (e.g., Real Options).

Observation:

Beyond their respective particular assumptions, each of these generic methods shares a common deficiency in more general settings. Because a high granularity probability law is required, none of the available current methods/analyses is immediately extendable to decision making driven by valuation of flexibility.

Gap: What's out there? Will it work, here?

Summary:

- There is no useful definition of flexibility, and hence, no reported approach for capturing the uncertainty on value of flexibility.
- There are no off-the-shelf results for capturing uncertainty in the value of flexibility.
- There are no generic analytical methodologies that promise to be easily adapted to addressing decisions that consider the uncertain value of flexibility.
- There exists no empirical platform to exercise new/existing decision strategies that consider the uncertain value of flexibility.

Observation: We fully understand the deficiencies in the state-of-the-art with regarding to valuing flexibility.

Steps in advancing the state-of-the-art?

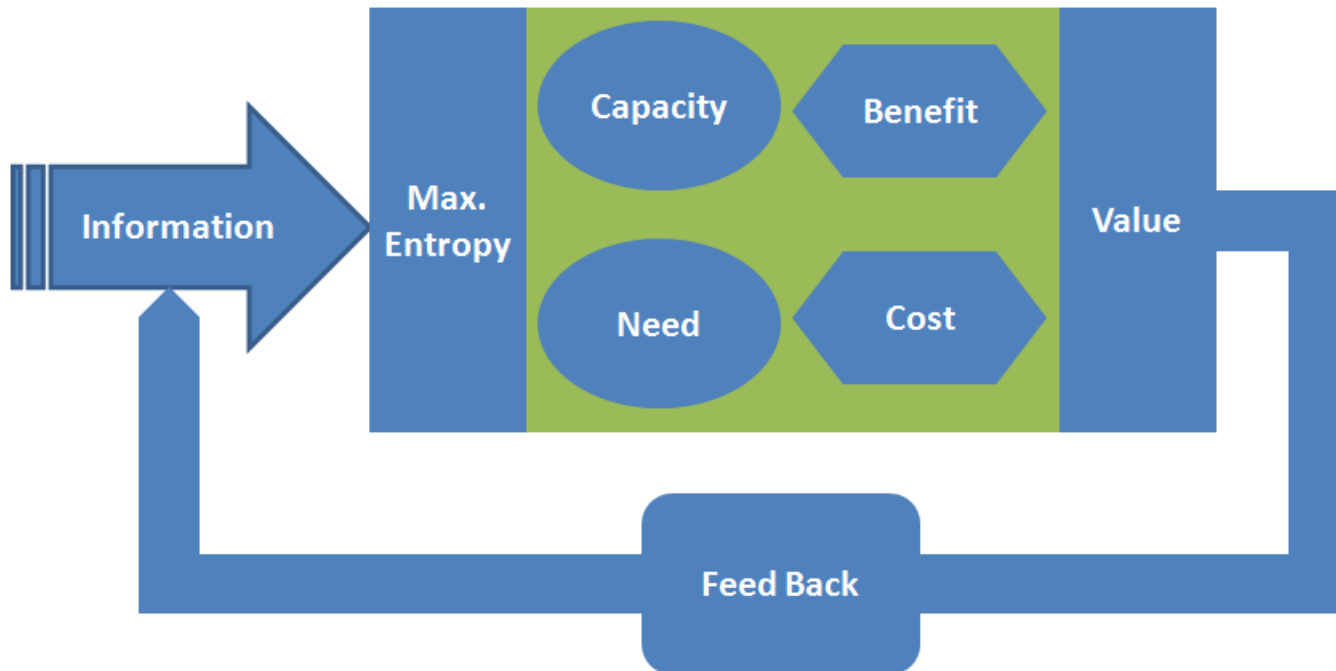
Summary:

- Advance an appropriate definition of flexibility.
- Develop an appropriate analytical framework in which decisions directed by value of flexibility can be addressed
- Develop an computational platform on which the usefulness of new modeling/analysis strategies can be tested. (Substantial effort, low risk)
- Develop practical new modeling/decision strategy that overcomes the curse of required high-granularity probability laws. (Substantial effort, higher risk)
- Develop decision support tools that implement realistic/practical decision support that values flexibility.

Predictive modeling and decision support:

- Accept the fact that in practice we will NEVER capture all finite joint probability distributions that govern the value of flexibility (i.e., complete probability law will be unavailable).
- Exploit the fact that not all uncertainty need be understood in order to identify optimal decisions that include the uncertain value of flexibility.
- Advance a deeper understanding of the relationship between design decisions and the value of information.
- Develop decision support that focuses on identifying the relative preference for flexibility using attainable (as opposed to desirable) predictive modeling.

Flexibility Valuation Tool



- Decision support for program development and management
- Help acquisition managers make best decision about the introduction of flexibility
- Rapid what/ifs
- Execute sensitivity with respect to information (information economics)
- Manage acquisition of information in procurement process

- Each decision epoch uses the best maximum-entropy estimate of risk associated with each alternatives
- Provides a measure of sensitivity to change in our underlying alternative risks with the acquisition of additional (perhaps costly) information
- Provides composable combinations of cost and value drivers, methods, probability distributions, mission scenarios, calibration data, outcome visualization capabilities

Project Results Overview

- **Successful project workshop in July**
 - Overall framework converged
- **Thorough state-of-the-art review**
- **Several approaches being pursued**
- **Some initial useful models, tools, and case studies developed**
 - Total Ownership Cost for foreseeable change cases
 - Knowledge Value Added/Risk/Real Options; SHIPMAIN cases
 - New value based flexibility framework
- **Plans to extend, unify approaches and tools**
 - Methods, data, case studies
 - Address unforeseeable change
 - Gap and opportunity analyses
 - Unified flexibility analysis toolset

Plans and Priorities for Phase 2 (March 2011)

- Cross-fertilize, extend current valuation methods and tools
 - Coherent analytical framework for valuing flexibility
 - Calibrate to each others' data
- Assess improved methods and tools for *achieving* flexibility
- Prototype unified flexibility analysis toolset
- Provide methods and tools to Systems 2020 pilots to assess utility, obtain improvement insights
 - Tailor current methods and tools to support upcoming decision situations
- Explore use of self-adaptive project and change traffic monitoring, synthesis of recommender systems for adaptation
 - Management-controllable cost/schedule driver adjustment
 - Time-determined development (DSB, 2007): add or drop borderline-priority features to meet cost/schedule targets
- Present results, obtain feedback at NDIA SE conference, SERC Annual Research Review

Deliverables for Phase 2 (March 2011)

- Prototype integrated toolset
 - Inputs and outputs include those needed for total ownership cost, real options, knowledge value added, ...
 - Guidance and checklists for preparing inputs
 - Exercise alternative approaches with cases from different domains
- Calibration of toolset to data from different domains
 - Modular munitions
 - Ship maintenance
 - AEGIS
 - C4ISR
- Guidance and examples of use in making value-of-flexibility DoDI 5000.02 milestone decisions
 - Identification of when particular methods are appropriate
 - Specifying bounds on value of flexibility measure

Seeking Input from Key Constituents

Conversation Starters

- How do you currently make decisions regarding flexibility?
 - How much are you willing to pay for added flexibility?
 - What are the primary hurdles in valuing flexibility?
- What information do you need to value flexibility?
 - Is the information available?
 - If not, what are possible avenues of getting the information?
- How would you use tools for valuing flexibility?
 - What are the desired characteristics for such tools?
 - Who would use them?
 - ...

Background Slides

Flexibility - Definitions

- Flexibility is defined as the degree of responsiveness for any future change in a product design [Rajan et al.]⁶
- The ability of a system to adapt to uncertain internal or external changes affecting its value delivery, in a timely and cost-effective manner. In other words, flexibility is the ease with which changes in value delivery in a system can be addressed. Here ease refers to the cost-effectiveness of addressing change. [Nilchiani]⁸
- Distinction between ability to change within a state (adaptability) and ability to change from one state to another (flexibility) [Bordoloi et al.]¹⁰
- The ability of a system to change on demand, incorporating scalability, evolvability, maintainability, and adaptability [Brown and Eremenko]¹¹
- Adaptation is the enhancement or change of a fielded system and if such a change has a low cost-benefit ratio, as defined by the customer or market, the system is deemed flexible [Mark]¹²
- Reconfigurable system is one in which variables that can be changed as well as the range of their change are identified to improve the performance of the system [Ferguson and Lewis]¹³

Measures of flexibility

- Early design stage metric to rate flexibility of design using flow analysis tables [Cormier]¹⁴
- Use of entropic measure to measure routing flexibility for a job (part) [Yao]²⁹
- Program valuation technique based on Real Options Theory (geometric Brownian motion used to calculate $E[NPV]$) [Peoples]¹⁵
- Development of a measure of adaptability for products through the use of an adaptability factor representing the normalized savings achieved by adaptation versus dedicated product (applicable to new or existing designs) [Gu et al.]¹⁸
- Information-theoretic measures (entropic measure) to measure routing flexibility, operations flexibility and loading flexibility in a manufacturing system [Kumar]²⁸
- Measure of flexibility based on performance increase (output) corresponding to the required cost and time to realize the change [Mark]¹⁹
- Formal Methodology for the Evaluation of Design Alternatives (MEDA), rooted in classical utility theory, in order to evaluate and rank design alternatives early on in the design process [Thurston]¹⁷

Incorporating flexibility in systems

- **Modular Design**
 - Subordination of a system to a rational functional structure as an approach for increasing general adaptability (design for unforeseen events) [Hashemian]¹⁴
 - General design guidelines based on functions independence (clustering and modularization) [Gu et al.]¹⁸
 - Modular design to achieve adaptability without change propagation throughout the entire product [Chmarra et al.]²⁰
 - Clustering of components of an adaptable system based on Design Structure Matrices (DSM) [Arts et al.]²²
- **Product Family Development / Platform Design**
 - Development of a metric to assist with the evaluation of design options early on in the design process by rating the overall flexibility of the system using flow analysis tables [Cormier et al.]¹⁴
 - Two stage optimized design process for flexible product platform components, evaluated based on expected Net Present Value using Monte Carlo simulation [Suh]²⁵
 - Development of a framework to increase the system's flexibility of fielded products by evaluating Optimal Point Designs against Platform Based Derivatives. Evaluation is based on the performance gap of the two designs [Mark]¹⁹

Incorporating flexibility in systems

- Autonomous Adaptation
 - Development of an autonomous material flow system through the use of function-oriented modularization and intelligent multi-agent-systems to enable the system to react on events autonomously [Wilke]³⁰
 - Three-layer reference model for self-management systems based off the three-level robotic architectural model Control: reactive feedback control, Sequencing: reactive plan execution and Deliberation: planning developed by Gat [Kramer et al.]³¹
 - Service-oriented component model to support the construction and execution of component based applications that are capable of autonomously adapting at runtime due to the dynamic availability of the services provided by constituent components [Cervantes et al]³²
- Design Selection
 - Generalized purchase modeling approach to develop a Decision Support System (DSS) based on a customer expected utility metric to support the selection in product design [Besharati et al.]³⁴
 - Real Options concept to model risks and delayed decision benefits under uncertainty in technologies, etc. and development of a quantitative measure of the value (performance and cost) of different family designs to select the most appropriate design from all alternatives [Gonzalez-Zugasti et al.]³⁵
 - Staged deployment approach to introduce flexibility into a system using real options (where demand follows a geometric Brownian motion) to match the system evolution path to the actual unfolding demand scenario [De Weck]²⁷

Strategies for incorporating flexibility

- **Delayed differentiation/extensibility**
 - Flexibility conservation principle
 - Field programmability
- **Modularization/reconfigurability**
 - Optimal decomposition
 - Interface standardization
- **Robust optimization**
 - Maximizing range over which value proposition remains feasible
 - Graceful degradation
- **Options exercise games - intersection of real options analysis with game theory**
 - Flexibility as a measure of future options available
 - Key decisions are valuing the option and determining the execution time